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The Refractive Index Structure Parameter/Atmospheric Optical Turbulence Model: CN2

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The Refractive Index Structure Parameter/Atmospheric Optical Turbulence Model: CN2

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Abstract

The CN2 model is a semi-empirical algorithm that makes a quantitative assessment of atmospheric optical turbulence. The algorithm uses surface layer gradient assumptions applied to two levels of discrete vertical profile data to calculate the refractive index structure parameter. Model results can be obtained for unstable, stable, and near-neutral atmospheric conditions. The CN2 model has been benchmarked on data from the REBAL '92 field study. The model will shortly be added to the Electro-Optics Atmospheric Effects Library (EOSAEL). This report gives technical and user's guide information on the CN2 model.

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1. Introduction

Atmospheric optical turbulence is a problem for most electro-optical (EO) systems. The image distortion it promotes can drastically reduce system and sensor performance. A means of assessing the levels of optical turbulence, relying on calculations that require a minimum of atmospheric data, could be an advantage to those in the field of EO system design and application. This report introduces the CN2 model, a semi-empirical algorithm developed by the Army Research Laboratory (ARL) for inclusion into the Electro-Optics Atmospheric Effects Library (EOSAEL), which addresses the atmospheric optical turbulence problem.

The propagation of a light beam through the atmosphere is affected by random fluctuations in the refractive index of air (Kunkel et al., 1981). These fluctuations or discontinuities cause *optical turbulence*—variations in the speed at which the wavefront propagates. The refractive index structure parameter (C_n^2) is a quantitative measure of optical turbulence.

The value of C_n^2 has been generally observed to range from about 10^{-12} to 10^{-16} $m^{-2/3}$. High values of C_n^2, 10^{-12} $m^{-2/3}$ or greater, even over nominal distances, usually indicate turbulent atmospheres wherein considerable visual blurring or image distortion would be present (as if one were looking out over a hot paved road, over an airport runway, or, in an extreme case, through the exhaust behind a jet engine). At lower values of C_n^2, 10^{-16} to 10^{-15} $m^{-2/3}$, atmospheric optical turbulence would generally be considered negligible. (However, there could be other image-degrading effects arising from other factors, such as precipitation, fog, or smoke.)

Many simulation models have been developed that address optical turbulence in the atmospheric surface layer (Kunkel et al, 1981; Andreas, 1988; Miller and Ricklin, 1990; Tunick and Rachele, 1991; Sadot and Kopeika, 1992; Tofsted, 1993; and Rachele and Tunick, 1994); these models vary both in mathematical complexity and in the amounts and types of inputs and computer capabilities required. The CN2 model reported on here is a refractive index structure parameter model that makes a quantitative assessment of atmospheric optical turbulence given two levels of wind, temperature, and humidity profile data as input. It contains a surface layer profile structure algorithm derived by Rachele et al (1991, 1995, 1996a) that makes estimates of C_n^2 obtainable for unstable, stable, and near-neutral atmospheric conditions. CN2 also computes the surface heat and moisture flux.

This report gives a mathematical outline of the CN2 model, provides some user's guide information (sect. 4) on the new module intended for the EOSAEL, and provides output examples (sect. 5).

EOSAEL 95 is available at no cost to U.S. Government agencies, specified Allied organizations, and their authorized contractors. U.S. Government agencies needing EOSAEL 95 should send a letter of request, signed by a branch chief or division director, to the Army Research Laboratory (ARL). Contractors should have their Government contract monitors send the

letter of request. Allied organizations must request EOSAEL 95 through their national representatives. The EOSAEL point of contact at ARL is Dr. Alan Wetmore:

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Letters of request should include intended uses and the type of nine-track tape necessary for computer execution: ASCII, UNIX, tar format in 1600 or 6250 bpi, or SUN cartridge (EOSAEL 95 cannot be supplied on media other than these). Documentation for modules is included.

2. Mathematical Description of CN2 Model

The proposal to include CN2 in the EOSAEL was drafted only recently. The model itself, however, is based on a combination of concepts and algorithms that had been developed and partially validated over a number of years, such as those documented in Rachele et al (1991, 1995, 1996ab), Tunick and Rachele (1991), Rachele and Tunick (1992, 1994), and Tunick et al (1994). The motivation for these studies was principally to develop and verify a set of equations for the atmospheric stability portion of the calculations needed to evaluate an expression for C_n^2, such as the one given in Tatarski (1961), which can be written as

$$C_n^2(z) = b\,\frac{K_H}{\varepsilon^{1/3}}\left(\frac{\partial n}{\partial z}\right)^2 , \tag{1}$$

where b is equal to 3.2 and called the Obukhov-Corrsin constant, K_H is the turbulent exchange coefficient for heat diffusion, ε is the energy dissipation rate (Panofsky, 1968), and $\partial n/\partial z$ is the vertical gradient of the index of refraction, n. A list of symbols and constants is given in table 1.

For visible and IR wavelengths, the expression for $\partial n/\partial z$, as presented by Tunick and Rachele (1991), is based on work reported by Andreas (1988). Andreas's formulations, which are expressed in terms of gradients of temperature and *absolute* humidity, were modified to expressions in terms of gradients of potential temperature θ and *specific* humidity q, as required by Tatarski (1961). For the visible region and near-infrared wavelengths from 0.36 to 3 µm (as denoted by the subscript v), Andreas (1988) writes

$$n_v = 1 + \left(M_1(\lambda)\,\frac{P}{T} + 4.615\left(M_2(\lambda) - M_1(\lambda)\right)Q\right) \times 10^{-6} , \tag{2}$$

where

$$M_1(\lambda) = 23.7134 + \frac{6839.397}{130-\sigma^2} + \frac{45.473}{38.9-\sigma^2} , \tag{3}$$

and

$$M_2(\lambda) = 64.8731 + 0.58058\,\sigma^2 - 0.007115\,\sigma^4 + 0.0008851\,\sigma^6 . \tag{4}$$

Transforming equation (2) in terms of potential temperature (θ) and specific humidity (q) yields

$$n_v = 1 + \left(M_1(\lambda)\,\frac{P}{\theta-\gamma_d(z-z_r)} + 1.60948\left[M_2(\lambda) - M_1(\lambda)\right]\frac{Pq}{\theta-\gamma_d(z-z_r)}\right) \times 10^{-6} . \tag{5}$$

Table 1. List of symbols.

Symbol	Name or description	Value or equation	Literature reference
C_n^2	refractive index structure parameter	$C_n^2 = b\frac{K_H}{\varepsilon^{1/3}}\left(\frac{\partial n}{\partial z}\right)^2$	
b	Obukhov-Corrsin constant	3.2	Panofsky (1968), Wyngaard (1973), Andreas (1988), Hill (1989)
g	gravitational acceleration	$9.8\ \mathrm{m/s^2}$	—
k	von Karman's constant	0.4	Businger et al (1971)
K_H	turbulent exchange coefficient for heat	$K_H = u_* kz/\phi_H(\zeta)$	Businger et al (1971)
L	Obukhov scaling length	$L = u_*^2\theta/kg\theta_*$	Obukhov (1946)
$M_1(\lambda)$	constant in eq (6) and (11)	—	—
$M_2(\lambda)$	constant in eq (6)	—	—
n_i	index of refraction (infrared)	—	Andreas (1988)
n_{iw}	refractivity due to water vapor	—	Hill and Lawrence (1986)
n_V	index of refraction (visible)	—	Andreas (1988)
n_{Vd}	contribution from dry air to instantaneous refractivity	—	Owens (1967)
P	atmospheric pressure in millibars	—	—
q	specific humidity (kg/kg)	—	—
Q	absolute humidity ($\mathrm{kg/m^3}$)	—	—
T	air temperature (K)	—	—
V	wind velocity (m/s)	—	—
X	scaled wavelength	$10\ \mu\mathrm{m}/\lambda$	—
z	height (m) above ground	—	—
z_r	reference height above ground	2 m	—
θ_*	potential temperature scaling parameter	$\theta_* = \frac{k\Delta\theta}{\phi_H \Delta \ln z}$	Rachele et al (1995)

Table 1. List of symbols (cont'd).

Symbol	Name or description	Value or equation	Literature reference
θ_{v*}	potential temperature scaling parameter	$\theta_{v*} = \dfrac{k\Delta\theta_v}{\phi_H \Delta \ln z}$	Rachele et al (1995)
q_*	specific humidity scaling constant	$q_* = \dfrac{k\Delta q}{\phi_H \Delta \ln z}$	Rachele et al (1995)
u_*	friction velocity	$u_* = \dfrac{k\Delta V}{\phi_m \Delta \ln z}$	Rachele et al (1995)
z^*	logarithmic mean scaling height	$z^* = \dfrac{\Delta z}{\Delta \ln z}$	Rachele et al (1995)
α	scaled temperature	$T/273.15$	—
Δ	difference operator	(i.e., $\Delta\theta = \theta_2 - \theta_1$)	—
ε	energy dissipation rate	$\varepsilon = u_*^3 (\phi_m - \zeta)/kz$	Panofsky (1968)
λ_d	dry adiabatic lapse rate	-0.00098 °C/m	—
λ	wavelength (µm)	—	—
$\phi_H(\zeta)$	dimensionless temperature lapse rate	$\phi_H(\zeta) = (1 - 15\zeta)^{-1/2}$ for $\zeta < 0$ $\phi_H(\zeta) = 1 + 5\zeta$ for $\zeta > 0$	Dyer (1974), Hicks (1976) Webb (1970)
$\phi_m(\zeta)$	dimensionless wind shear	$\phi_m(\zeta) = (1 - 15\zeta)^{-1/4}$ for $\zeta < 0$ $\phi_m = \phi_H$ for $\zeta > 0$	Dyer (1974), Hicks (1976) Webb (1970)
ϕ_q	nondimensional specific humidity lapse	$\phi_q = \phi_H$	—
θ	potential temperature	$\theta \approx T + 0.0098 \times (z - z_r)$	Rachele and Tunick (1994)
θ_V	virtual potential temperature	$\theta_V = \theta(1 + 0.61q)$	Busch (1973)
σ	1/wavelength	λ^{-1}	—
ζ	scaling ratio	z/L	Monin and Obukhov (1954)
$\dfrac{\partial\theta}{\partial z}$	vertical gradient of potential temperature	$\dfrac{\partial\theta}{\partial z} = \dfrac{\theta_*}{kz}\phi_H$	Busch (1973)
$\dfrac{\partial\theta_v}{\partial z}$	vertical gradient of virtual potential temperature	$\dfrac{\partial\theta_v}{\partial z} = \dfrac{\theta_{v*}}{kz}\phi_H$	Busch (1973)

Table 1. List of symbols (cont'd).

Symbol	Name or description	Value or equation	Literature reference
$\frac{\partial q}{\partial z}$	vertical gradient of specific humidity	$\frac{\partial q}{\partial z} = \frac{q^*}{kz} \phi_H$	Busch (1973)
$\frac{\partial V}{\partial z}$	vertical gradient of wind velocity	$\frac{\partial V}{\partial z} = \frac{u_*}{kz} \phi_m$	Busch (1973)
$[A]$, $[B]$	placement variables in eq (11)	—	—
$\partial n / \partial z$	vertical gradient of mean refractive index	—	Tunick and Rachele (1991)
$\frac{\partial n_i}{\partial z}$	vertical gradient of index of refraction (infrared)	—	Tunick and Rachele (1991)
$\frac{\partial n_v}{\partial z}$	vertical gradient of index of refraction (visible)	—	Tunick and Rachele (1991)

For steady-state, homogeneous conditions, equation (5) yields

$$\frac{\partial n_v}{\partial z} = \left(- M_1(\lambda) \frac{P}{T^2} - 1.61 \left(M_2(\lambda) - M_1(\lambda) \right) \frac{Pq}{T^2} \right) \times 10^{-6} \frac{\partial \theta}{\partial z}$$
$$+ 1.61 \left(M_2(\lambda) - M_1(\lambda) \right) \frac{P}{T} \times 10^{-6} \frac{\partial q}{\partial z} \ . \tag{6}$$

For IR wavelengths from 7.8 to 19 μm (as denoted by the subscript i) Andreas (1988) (who refers to Hill and Lawrence (1986) and Owens (1967)) writes

$$n_i = 1 + (n_{vd} + n_{iw}) \times 10^{-6} \ , \tag{7}$$

where in the range from –40.0 to +40.0 °C,

$$n_{iw} = Q \left[\frac{957. - 928.\alpha^{0.4} (X - 1)}{1.03\alpha^{0.17} - 19.8X^2 + 8.2X^4 - 1.7X^8} + \frac{3.747 \times 10^6}{12{,}499. - X^2} \right] \ , \tag{8}$$

and

$$n_{vd} = M_1(\lambda) \frac{P}{T} - 4.615\, M_1(\lambda)\, Q \ . \tag{9}$$

Substituting Q (kg/m^{-3}) = 0.34875 Pq/T into equations (8) and (9), and taking the derivative of equation (7) in terms of θ and q gives

$$\frac{\partial n_i}{\partial z} = \left(- M_i(\lambda)\,\frac{P}{T^2} - 1.6095\,M_i(\lambda)\,\frac{Pq}{T^2} + 0.34875\,\frac{Pq}{T}\,[A] - 0.34875[B]\,\frac{Pq}{T^2} \right) \times 10^{-6}\,\frac{\partial \theta}{\partial z}$$

$$+ \left(0.34875[B] - 1.6095\,M_1(\lambda)\right)\frac{P}{T} \times 10^{-6}\,\frac{\partial q}{\partial z}\ , \qquad (10)$$

where

$$[A] = \left(- \frac{1.359\alpha^{-0.6}\,(X-1)}{1.03\alpha^{0.17} - 19.8X^2 + 8.2X^4 - 1.7X^8} + \frac{0.5949\alpha^{0.43}\,(X-1)}{\left(1.03\alpha^{0.17} - 19.8X^2 + 8.2X^4 - 1.7X^8\right)^2} \right) \qquad (11)$$

and

$$[B] = \left[\frac{957. - 928.\alpha^{0.4}\,(X-1)}{1.03\alpha^{0.17} - 19.8X^2 + 8.2X^4 - 1.7X^8} + \frac{3.747 \times 10^6}{12499. - X^2} \right]\ . \qquad (12)$$

The surface layer algorithm called MARIAH (Rachele et al, 1991, 1995, 1996a,b) is used to obtain a noniterative solution for the temperature and moisture partial derivatives $\partial\theta/\partial z$ and $\partial q/\partial z$. The MARIAH algorithm is based on a series of concepts more commonly known as similarity theory (as defined by the earlier efforts discussed in Obukhov (1946), Monin and Obukhov (1954), Businger et al (1971), and Busch (1973)).

As similarity theory prescribes, the partial derivatives of wind speed, temperature, and moisture with respect to height can be written as

$$\frac{\partial V}{\partial z} = \frac{u_*}{kz}\,\phi_m\ , \quad \frac{\partial \theta}{\partial z} = \frac{\theta_*}{kz}\,\phi_H\ , \quad \frac{\partial q}{\partial z} = \frac{q_*}{kz}\,\phi_q\ , \qquad (13)$$

where V is wind speed (m/s), u_* is the friction velocity (m/s), θ_* is the potential temperature scaling constant (K), q_* is the specific humidity scaling constant (g/g), z is height above ground, k is Karman's constant (0.4), and ϕ_m, ϕ_H, and ϕ_q are the dimensionless wind shear, dimensionless temperature lapse rate, and dimensionless humidity lapse rate, respectively. The MARIAH algorithm suggests that the partial differential equations in equation (13) can be re-expressed as

$$u_* = \frac{k\Delta V}{\phi_m \Delta \ln z}\ , \quad \theta_* = \frac{k\Delta\theta}{\phi_H \Delta \ln z}\ , \quad q_* = \frac{k\Delta\,q}{\phi_H \Delta \ln z}\ , \qquad (14)$$

where the Δ operator refers to the difference in data taken from one tower level to another (i.e., $V_2 - V_1$). Here, the dimensionless term for humidity is assumed equal to the dimensionless temperature lapse (i.e., $\phi_q = \phi_H$), even though field observations have shown that atmospheric gradients of temperature do not always or universally behave similarly to those of moisture. The relationships in equation (14) can be handled in a straight-

forward manner, given expressions for the dimensionless shear and lapse rate terms. Following Dyer (1974) and Hicks (1976), I use

$$\phi_m = \left[1 - 15(z/L)\right]^{-1/4} \text{ and } \phi_H = \left[1 - 15(z/L)\right]^{-1/2} \tag{15}$$

for unstable atmospheric conditions, and from Webb (1970), I use

$$\phi_m = \phi_H = 1 + 5(z/L) \ , \tag{16}$$

for stable atmospheric conditions. Busch (1973) defines the Monin-Obukhov (M-O) scaling ratio as

$$\frac{z}{L} = k\frac{g}{\theta_v}\frac{\theta_{v*}}{u_*^2} z \ , \tag{17}$$

where $\theta_V = \theta(1 + 0.61q)$ is the virtual potential temperature, and $\theta_{v*} = \theta_* + 0.61\theta q_*$ is the virtual potential temperature scaling constant. (This equation for the M-O scaling ratio, which reflects atmospheric stability in terms of the scaling constants in eq (14), includes the effects of water (vapor) content by considering the dry or virtual atmosphere. The virtual temperature is the temperature that dry air must have to equal the density of moist air at the same pressure (Stull, 1988).) Therefore, from equations (14) and (17), the expression for the Obukhov length L used in equations (15) and (16) can be formulated as

$$L = \frac{1}{\Delta \ln z}\frac{\theta_v}{g}\frac{(\Delta V)^2 \phi_H}{[\Delta\theta + 0.61\,\theta\Delta\, q]\,\phi_m^2} \ , \tag{18}$$

so that for unstable atmospheric conditions,

$$L = \frac{1}{\Delta \ln z}\frac{\theta_v}{g}\frac{(\Delta V)^2}{\Delta\theta + 0.61\,\theta\Delta\, q} \ . \tag{19}$$

For stable atmospheric conditions, it can be expressed as

$$L\phi_m = \frac{1}{\Delta \ln z}\frac{\theta_v}{g}\frac{(\Delta V)^2}{\Delta\theta + 0.61\,\theta\Delta\, q} \ . \tag{20}$$

Note that the gradients for each layer should be taken to mean those tangent to the indicated profiles at $z = z^*$, where $z^* = \Delta z/(\Delta \ln z)$, instead of $z^* = (z_1 \cdot z_2)^{1/2}$, the geometric mean, which is almost always assumed (Rachele and Tunick, 1991; Rachele et al, 1991). The relationships for profiles of C_n^2, which are generally accepted for $z \leq |L|$, can be expressed as

$$C_n^2(z) = C_n^2(z^*) \cdot \left(\frac{z}{z^*}\right)^{-4/3} \text{ and } C_n^2 = C_n^2(z^*) \cdot \left(\frac{z}{z^*}\right)^{-2/3} \ , \tag{21}$$

for unstable and stable or near-neutral atmospheric conditions, respectively, where the –4/3 and –2/3 behavior had been indicated by experimental surface layer data (as discussed in somewhat more detail by Wyngaard, 1973, and Wyngaard and LeMone, 1980).

3. Verification

The CN2 model was benchmarked using the data collected during the field study entitled "Radiation Energy Balance Experiment for Imagery and EM Propagation" (REBAL '92). REBAL '92 (Tunick et al, 1994) was conducted during May and July 1992 at Bushland, TX (35°N latitude, 102°W longitude, 1170-m elevation above mean sea level) by the Army Research Laboratory and the Conservation and Production Research Laboratory (CPRL) of the USDA Agricultural Research Service (ARS). (The test site at ARS-CPRL in Bushland, TX, is approximately 16 km due west of Amarillo.) Diurnal measurements of sky and emitted radiation, soil heat flux, soil temperature and volumetric water content, evaporation, optical turbulence (from a scintillometer*), near- and far-field infrared imager data, and micrometeorological profile data were collected over wet and dry bare soil for clear and cloudy sky conditions.

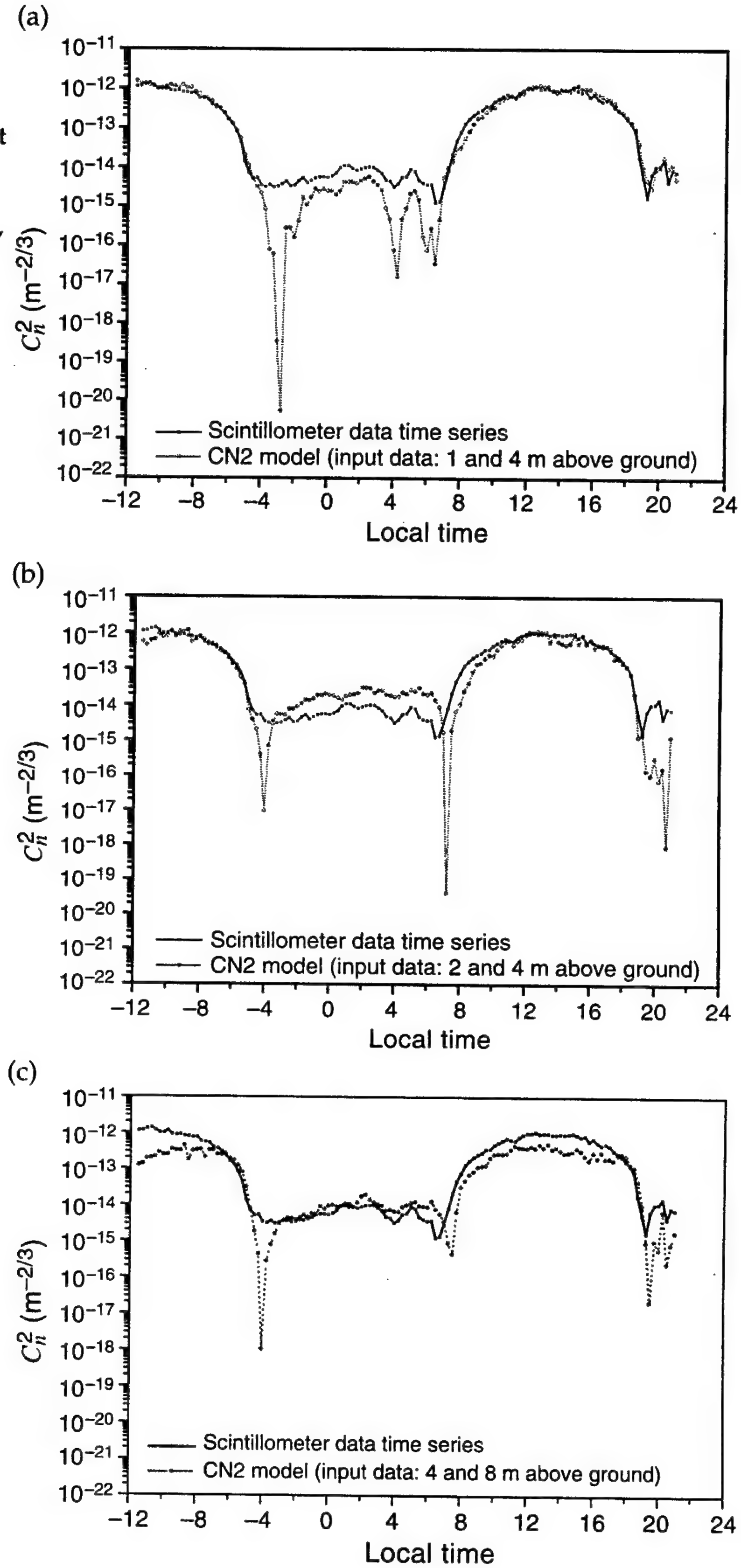
The micrometeorological profiles of wind speed, temperature, and relative humidity were measured on an 8-m tower centered in the test area (at 0.5, 1., 2., 4., and 8. m above the surface). A 0.94-μm scintillometer (Lockheed Engineering & Management IV-L) source module was mounted 2 m above ground on a tripod at the north end of the test area and was aligned and focused down-field (i.e., to the south) over a path of approximately 450 m.

Figure 1 shows time series from CN2 model results compared to time series of the observed data. Each plot reflects conditions during the same collection interval (i.e., 8 July 1992, 1230 local time (LT), to 9 July 1992, 2100 LT), except that the wind speed, temperature, and relative humidity input data (15-min averaged) are taken from different heights above ground (that is, 1 and 4 m, 2 and 4 m, and 4 and 8 m above ground, respectively).

Overall, the C_n^2 estimates appear to be in line with the observations. However, there are several instances when the CN2 model results are in extreme contrast to the scintillometer data. These occur numerically when the computed temperature gradients are very, very small: small enough to cause singularities in the model calculations. They occur physically during periods, however brief, of near-neutral or neutral atmospheric stability. Figure 2 is a time series of temperature data, measured at four heights above ground level. Segments of the data (indicated on the figure by arrows) illustrate where differences in temperature from one level to the next (i.e., the gradients) are slight and nearly impossible to distinguish. Apparently, the CN2 model's "local-gradient" approach tends to exaggerate the near-zero- and zero-gradient situations. Future studies using more complex sets of equations for the atmosphere may help to improve upon turbulence assessments at these times.

**Scintillometers are ground-based, remote-sensing instruments designed to measure optical turbulence intensity along a line-of-sight path established between a transmitter and a downrange receiver. Scintillometer operation is based on the principle that scintillations or light intensity variations occur as atmospheric density discontinuities create refraction effects in light propagating along a path (Clifford et al, 1974). The refractive index structure parameter C_n^2 is related to the intensity of these refraction effects.*

Figure 1. Time series of scintillometer data compared to CN2 model output, determined from input data at (a) 1 and 4 m above ground, (b) 2 and 4 m above ground, and (c) 4 and 8 m above ground.



Finally, the time series analysis of temperature gradients shown in figure 3 implies that the most unstable gradients were described by data closer to the ground (resulting in higher estimates of optical turbulence during daytime hours). However, these data did not describe the greater stable gradients. An unexpected result from this study (as indicated in the figure by the solid squares) was that the greater stable gradients (and estimates of C_n^2) for much of the nighttime hours were described by data from 2 and 4 m.

Figure 2. Time series of temperature data collected during REBAL '92 field study, 8–9 July 1992.

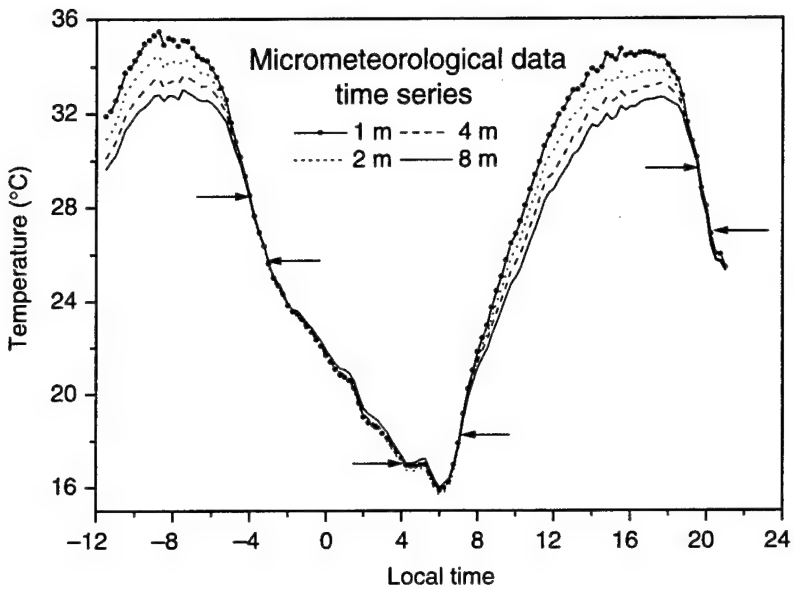
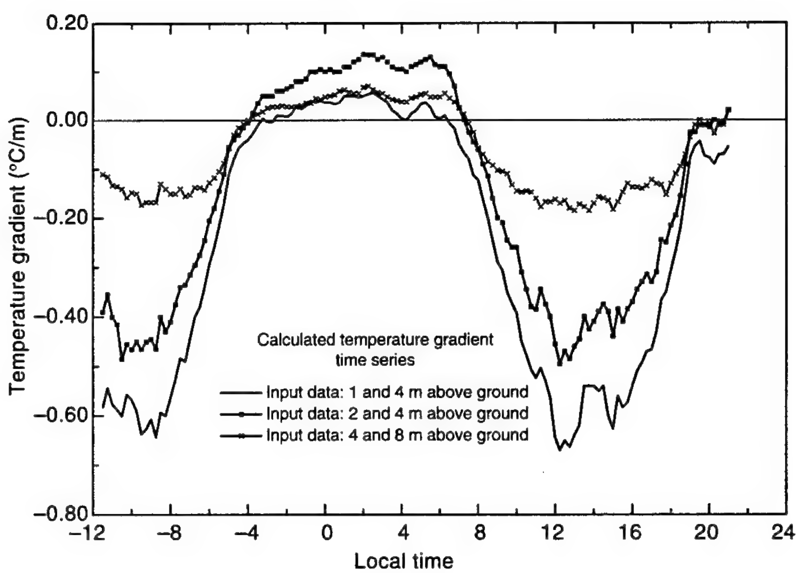


Figure 3. Time series of calculated temperature gradients from data collected during REBAL '92 field study, 8–9 July 1992.



4. CN2 Module User's Information

CN2 is one of several new modules that ARL is developing for inclusion into the EOSAEL. This state-of-the-art computer library comprises fast-running, theoretical, semi-empirical, and empirical computer programs that mathematically describe aspects of electromagnetic propagation in battlefield environments. The modules are connected through an executive routine, but are often exercised individually (Wetmore et al, 1997).

There are four input file records (referred to as "input cards") that contain the wavelength and meteorological data for the CN2 model calculations. Two additional cards (not shown) control program execution. Table 2 gives descriptions of the CN2 model input cards, along with range restrictions recommended for the parameters that these cards control.

Table 2. CN2 model input cards and parameter range restrictions.

Card	Identifier	Variable	Description	Recommended range restrictions
1	WAVE	WV	Wavelength (μm)	Visible: 0.36 μm ≤ WV ≤ 3.0 μm IR: 7.8 μm ≤ WV ≤ 19.0 μm
2	DATM	PR	Atmospheric pressure (mb) (at surface or either measurement height)	700 mb ≤ PR ≤ 1060 mb
3	LVL1	HGHT1	Height (m) above ground level, level 1 data	HGHT1 ≤ HGHT2 ≤ 20 m HGHT1 ≠ HGHT2 HGHT1 ≥ 0.5 m HGHT2 ≥ 1.0 m 0.5 m ≤ HGHT2 – HGHT1 ≤ 18.0 m
		TEMP1	Temperature (°C) at HGHT1	TEMP1 ≠ TEMP2 –40.0 °C ≤ (TEMP1, TEMP2) ≤ +40.0 °C
		WSPD1	Wind speed (m/s) at HGHT1	WSPD1 < WSPD2 0.0 m/s ≤ WSPD1 ≤ 18.0 m/s 1.0 m/s ≤ WSPD2 ≤ 18.0 m/s
		RHUM1	Relative humidity (%) at HGHT1	0% ≤ (RHUM1, RHUM2) ≤ 100%
4	LVL2	HGHT2 TEMP2 WSPD2 RHUM2	(parallel to LVL1 variables above)	(see above)

5. Input/Output Examples

In this section, I present examples of the input cards and formatted output produced by the CN2 model for the three general categories of atmospheric conditions: unstable, stable, and near-neutral atmospheric conditions. The following is the input file required for the three examples:

```
DATM     891.6     "Example 1"
LVL1       1.0     33.44     5.39     30.2
LVL2       4.0     31.42     6.35     32.9
WAVE        .94
GO
DATM     893.5     "Example 2"
LVL1       1.0     18.73     2.77     64.0
LVL2       4.0     19.06     3.80     64.6
GO
DATM     892.8     "Example 3"
LVL1       1.0     16.25     2.88     74.04
LVL2       4.0     16.20     3.72     75.05
DONE
```

5.1 Calculation for Unstable Atmospheric Conditions

Example 1 takes meteorological data from the REBAL '92 field study for 9 July 1992 at 1330 LT. The input data are representative of typical mid-afternoon, clear sky, unstable atmospheric conditions. The surface heat and moisture flux calculations reflect intense gradients of surface layer temperature and specific humidity. The computed C_n^2 at 2 m is on the order of 10^{-12}.

```
WAVELENGTH                        .94          MICRONS
ATMOSPHERIC PRESSURE           891.60          MB
LEVEL1 METEOROLOGY AT            1.00          METERS
AIR TEMPERATURE                 33.44          C
WINDSPEED                        5.39          M/S
RELATIVE HUMIDITY               30.20          %

LEVEL2 METEOROLOGY AT            4.00          METERS
AIR TEMPERATURE                 31.42          C
WINDSPEED                        6.35          M/S
RELATIVE HUMIDITY               32.90          %

SURFACE HEAT FLUX              468.01          W/M^2
SURFACE MOISTURE FLUX           46             W/M^2

"UNSTABLE ATMOSPHERE"
TEMPERATURE GRADIENT           -.6635E+00      DEGK/M
MOISTURE GRADIENT              -.1188E-03      G/G/M
```

REFRACTIVE INDEX STRUCTURE PARAMETER = CN^2 M^(-2/3)

Z=1	Z=2	Z=5	Z=10	Z=15	Z=20
3.843E-12	1.525E-12	4.495E-13	1.784E-13	1.039E-13	7.079E-14

5.2 Calculation for Stable Atmospheric Conditions

Example 2 takes meteorological data from the REBAL '92 field study for 9 July 1992 at 0200 LT. The input data are representative of typical night-time atmospheric conditions under mostly cloudless skies. The calculated heat flux reflects a slight surface inversion in temperature within this weakly stable layer. The computed C_n^2 at 2 m is on the order of 10^{-14}.

WAVELENGTH	.94	MICRONS
ATMOSPHERIC PRESSURE	893.50	MB
LEVEL1 METEOROLOGY AT	1.00	METERS
AIR TEMPERATURE	18.73	C
WINDSPEED	2.77	M/S
RELATIVE HUMIDITY	64.00	%
LEVEL2 METEOROLOGY AT	4.00	METERS
AIR TEMPERATURE	19.06	C
WINDSPEED	3.80	M/S
RELATIVE HUMIDITY	64.60	%
SURFACE HEAT FLUX	-20.07	W/M^2
SURFACE MOISTURE FLUX	-42.07	W/M^2
"STABLE ATMOSPHERE"		
TEMPERATURE GRADIENT	.1198E+00	DEGK/M
MOISTURE GRADIENT	.1005E-03	G/G/M

REFRACTIVE INDEX STRUCTURE PARAMETER = CN^2 M^(-2/3)

Z=1	Z=2	Z=5	Z=10	Z=15	Z=20
3.619E-14	2.280E-14	1.238E-14	7.798E-15	5.951E-15	4.912E-15

5.3 Calculation for Near-Neutral Atmospheric Conditions

Example 3 takes meteorological data from the REBAL '92 field study for 9 July 1992 at 0630 LT. The input data are representative of typical atmospheric conditions that tend to occur daily within an hour after sunrise. During this interval of time, there is almost always at least one instance of a near-neutral lapse in temperature as the ground warms with increasing amounts of incident solar radiation that begins to break up the nighttime inversion. The calculated surface fluxes at this time are small. The computed C_n^2 at 2 m is on the order of 10^{-17}.

```
WAVELENGTH                           .94            MICRONS

ATMOSPHERIC PRESSURE              893.00            MB

LEVEL1 METEOROLOGY AT               1.00            METERS
AIR TEMPERATURE                    16.25            C
WINDSPEED                           2.88            M/S
RELATIVE HUMIDITY                  74.04            %

LEVEL2 METEOROLOGY AT               4.00            METERS
AIR TEMPERATURE                    16.20            C
WINDSPEED                           3.72            M/S
RELATIVE HUMIDITY                  75.05            %

SURFACE HEAT FLUX                   1.45            W/M^2
SURFACE MOISTURE FLUX             -17.62            W/M^2

"NEAR-NEUTRAL ATMOSPHERE"
TEMPERATURE GRADIENT                -.6866E-02      DEGK/M
MOISTURE GRADIENT                    .3327E-04      G/G/M

REFRACTIVE INDEX STRUCTURE PARAMETER = CN^2    M^(-2/3)
-----------------------------------------------------
  Z=1       Z=2       Z=5       Z=10      Z=15      Z=20
-----------------------------------------------------
5.856E-17 3.689E-17 2.003E-17 1.262E-17 9.628E-18 7.948E-18
-----------------------------------------------------
```

6. Summary

The CN2 model will shortly be added to the Electro-Optics Atmospheric Effects Library (EOSAEL). By applying surface layer gradient assumptions for two levels of wind, temperature, and humidity profile data to the calculation of the refractive index structure parameter C_n^2, the CN2 model makes a quantitative assessment of atmospheric optical turbulence. The model was benchmarked on REBAL '92 field study data. CN2 will be made available to U.S. Government agencies, specified allied organizations, and their authorized contractors through ARL's EOSAEL point of contact, Alan Wetmore.

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The CN2 model is a semi-empirical algorithm that makes a quantitative assessment of atmospheric optical turbulence. The algorithm uses surface layer gradient assumptions applied to two levels of discrete vertical profile data to calculate the refractive index structure parameter. Model results can be obtained for unstable, stable, and near-neutral atmospheric conditions. The CN2 model has been benchmarked on data from the REBAL '92 field study. The model will shortly be added to the Electro-Optics Atmospheric Effects Library (EOSAEL). This report gives technical and user's guide information on the CN2 model.

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